BALL MOUNTAIN DAM

JAMAICA, VERMONT

FINAL

REPORT ON THE

FIRST THREE CAMPAIGNS

Prepared for
Geotechnical Engineers, Inc.
by
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EXECUTIVE SUMMARY

This report describes the design, execution and findings of the first three campaigns of Boston Survey Consultants' deformation monitoring program.

The design of the monitoring scheme was completed in early 1986. The installation of the monitoring stations was undertaken during the period May 7 through June 7, 1986. The first series of measurements was completed in July 1986 while the remaining two campaigns took place in September and November of the same year.

A detailed analysis of the observation data has revealed small horizontal movements of a number of the monitored points. Several stations situated on or near the crest edge have undergone horizontal downstream displacements of a few millimetres (1mm - 4mm) while movements of similar magnitude have been detected at two other locations. No significant vertical movements have been identified.

Three further campaigns have been scheduled to take place during 1987. It is anticipated that the additional information gained from these measurements will give a coherent picture of the deformation trends.

1. INTRODUCTION

This report describes the design, measurement, adjustment and deformation analysis phases of the first three epochs of the geodetic monitoring scheme. It has been arranged in three parts. This volume includes the written report, Volume II contains the single epoch adjustment results and Volume III includes the deformation analyses. Seven plans accompany the report. The first shows the topography of the dam site as well as the location of the reference and object points. The remaining plans relate to the deformation analysis.

Network adjustments were performed using the Geodetic Network Adjustment (GNA) program while the Localization and Analysis of Deformations (LAD) software was employed for the deformation analysis. Both are products of Intergraph Corporation. All the statistical tests in the deformation analysis have been performed at the 95% level of confidence. Thus a horizontal displacement is "statistically significant at the 95% level of confidence" if the displacement vector extends beyond the perimeter of the 95% confidence region (ellipse). Similarly, a vertical displacement is significant at the 95% level of confidence if the vector extends beyond the vertical 95% confidence interval.

2. NETWORK DESIGN AND PRE-ANALYSIS

The network design and pre-analysis are interdependent undertakings. The pre-analysis is concerned with the network configuration, the type, number and quality of the observables, the computational requirements and the specification of equipment and observing procedures.

In the case of Ball Mountain Dam, the network configuration is severely constrained by the nature of the site which is characterized by extremely rugged terrain and extensive forest. The final reference network consists of five pillars, a Corps of Engineers disk set in the abutment of the spillway and an additional reference station situated on top of the intake tower. (see Plan #1). The disk (P6) and tower (1218) stations are treated as object points during the deformation analyses.

In the pre-analysis, consideration was given to the detection of single point displacements both on the dam structure (object points) <u>and</u> in the reference network (reference points). Note that the reference points are presumed to be unstable from one campaign to the next (In the first step of each deformation analysis they are tested for stability at the 95% level of confidence).

A tolerance limit of 3mm at the 95% level of confidence was employed in the pre-analysis. Thus, any single point displacement exceeding 3mm in either the horizontal (x,y) or vertical (z) should be detected as significant at the 95% level of confidence. The pre-analysis was undertaken by a team from the University of New Brunswick led by Dr. Adam Chrzanowski. (Chrzanowski et al., 1985). The following two sections summarize the salient features of the pre-analysis.

2.1 THE HORIZONTAL MONITORING SCHEME

In the final design, all possible directions were to be measured from stations P1, P2, P3, P4 and P5. At the time of the first campaign, it was decided to take additional observations from P6. Four distances were to be measured from P4 to P2, P3, P5 and P6.

The accuracy requirements for the observables are:

- o directions: std. dev. = +/- 0.5"
- o distances: std. dev. = +/- 5mm +/- 5ppm

Figure 2.1 shows the results of the horizontal preanalysis. The directions are to be measured in 4 sets using an electronic theodolite such as the Wild T2000 or Kern E2. As Chrzanowski et al., (1985) point out this accuracy can be attained only if certain observing precautions are adhered to. These include shading the theodolite from direct sunlight, using mechanical forced centering for the theodolite and targets, using specially designed targets, and measuring the tilt of the vertical axis. The distances are required to be measured using a suitable electro-optical distance measuring instrument (EODMI). This should be calibrated for zero error and scale and, if necessary, for cyclic error. Appropriate equipment must be employed for measuring the dry bulb temperature and atmospheric pressure.

Ordinary Wild traversing targets are used on the 27 object points and at P6. Special conical, omni-directional targets (Figure 2.2) are employed on the tower and at points P1 through P5. These were designed and produced under contract by the Dept. of Surveying Engineering at the University of New Brunswick.

2.2 THE VERTICAL MONITORING SCHEME

The vertical monitoring program requires that all zenith angles from stations P1 through P5 be measured to a standard deviation of 0.7". This can be achieved if 4 sets are observed and if the same precautions are adhered to as those listed in Section 2.1 above. Theodolite and target heights must be measured to an accuracy of at least 1mm.

2.3 REFRACTION

Chrzanowski et al., (1985) have emphasized that the ability of the monitoring scheme to detect vertical displacements may be severely degraded by changes in the coefficient of refraction from one campaign to the next. At their suggestion, temperature profile measurements were taken during each of the three campaigns observed to date. A preliminary analysis of these data attests to the severity of this problem (see Appendix IC).

2.4 MONUMENTATION

Three kinds of monument were planned (Figures 2.3, 2.4 and 2.5). In the case of the reference pillars, the design reflects the need for an observing platform which it is hoped will remain stable from one epoch to the next. Note the forced-centering socket which ensures precise horizontal relocation of the theodolite. The benchmark provides a reference point for the vertical network. During each campaign, the pillars are wrapped in 5cm thick foam rubber in order to minimize the distortions which may be induced by temperature imbalances.

The slope and crest monuments are designed in such a way that they will adequately represent local movements in their vicinity. To ensure that they are visible from the reference points, the slope monuments protrude approximately 1m above the rockfill slope. For the same reason, removable 0.5m extension rods are inserted in the crest monuments during the observing process. In order to ensure precise forced-centering, Wild GRT10 stems were grouted into the tops of these monuments. These match the removable Wild traversing targets, and extension rods.

The substratum associated with each pillar and monument is listed in Table 2.1.

TABLE 2.1

Summary of Pillar and monument Installations

POINT	SUBSTRATUM
P1	bedrock
P2	bedrock
P3	glacial till
P4	bedrock
P5	bedrock
P6	concrete retaining wall
11,12,13 21,22,23 31,32,33	gravel fill on dam crest
14-19,24-29,34-39	rock fill on downstream slope
1218	on top of concrete intake tower

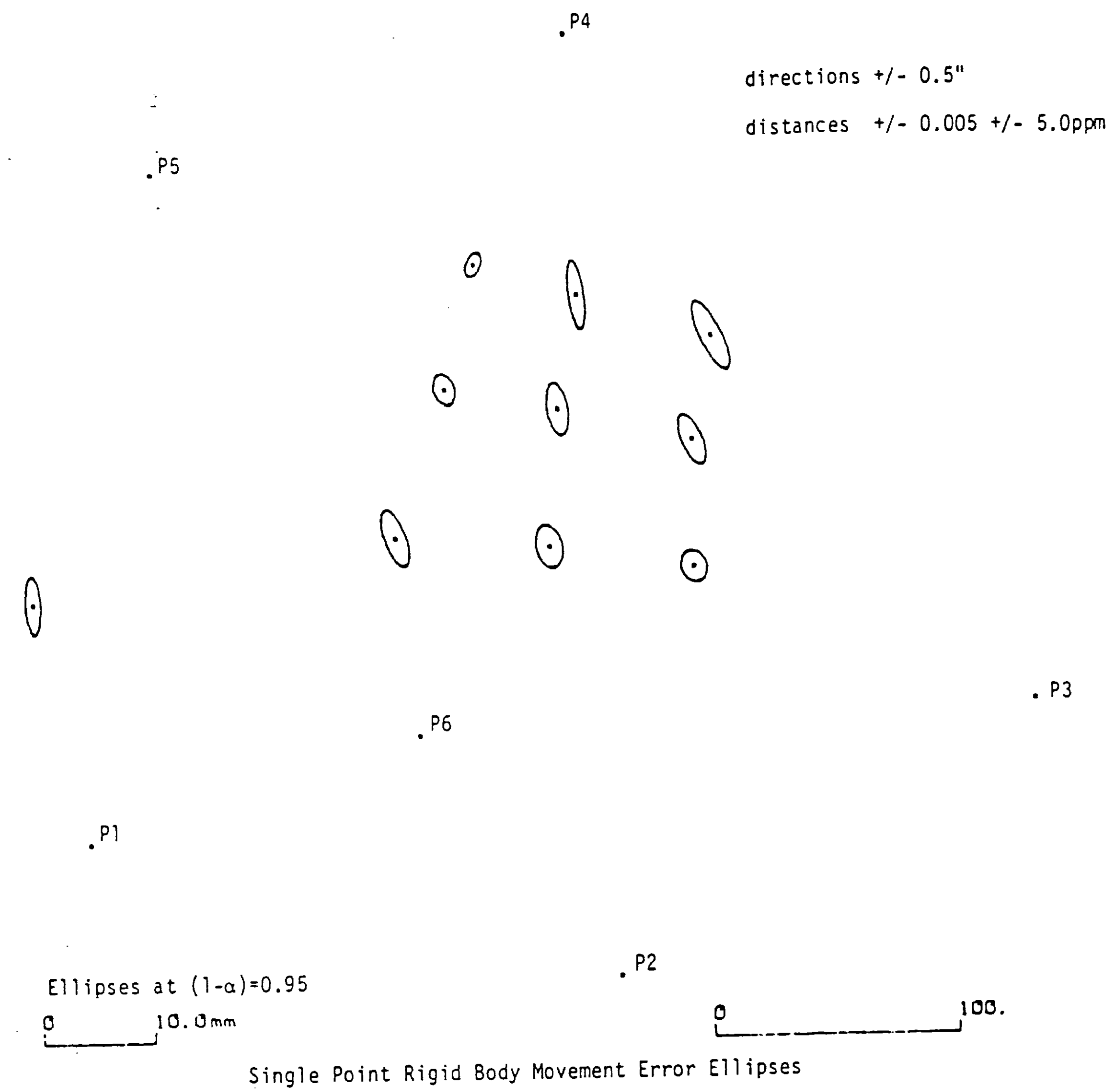


Figure 2.1 Horizontal pre-analysis after Chrzanowski et al. (1985) Note that the final position of P3 differs slightly from that shown here (see Plan #1)

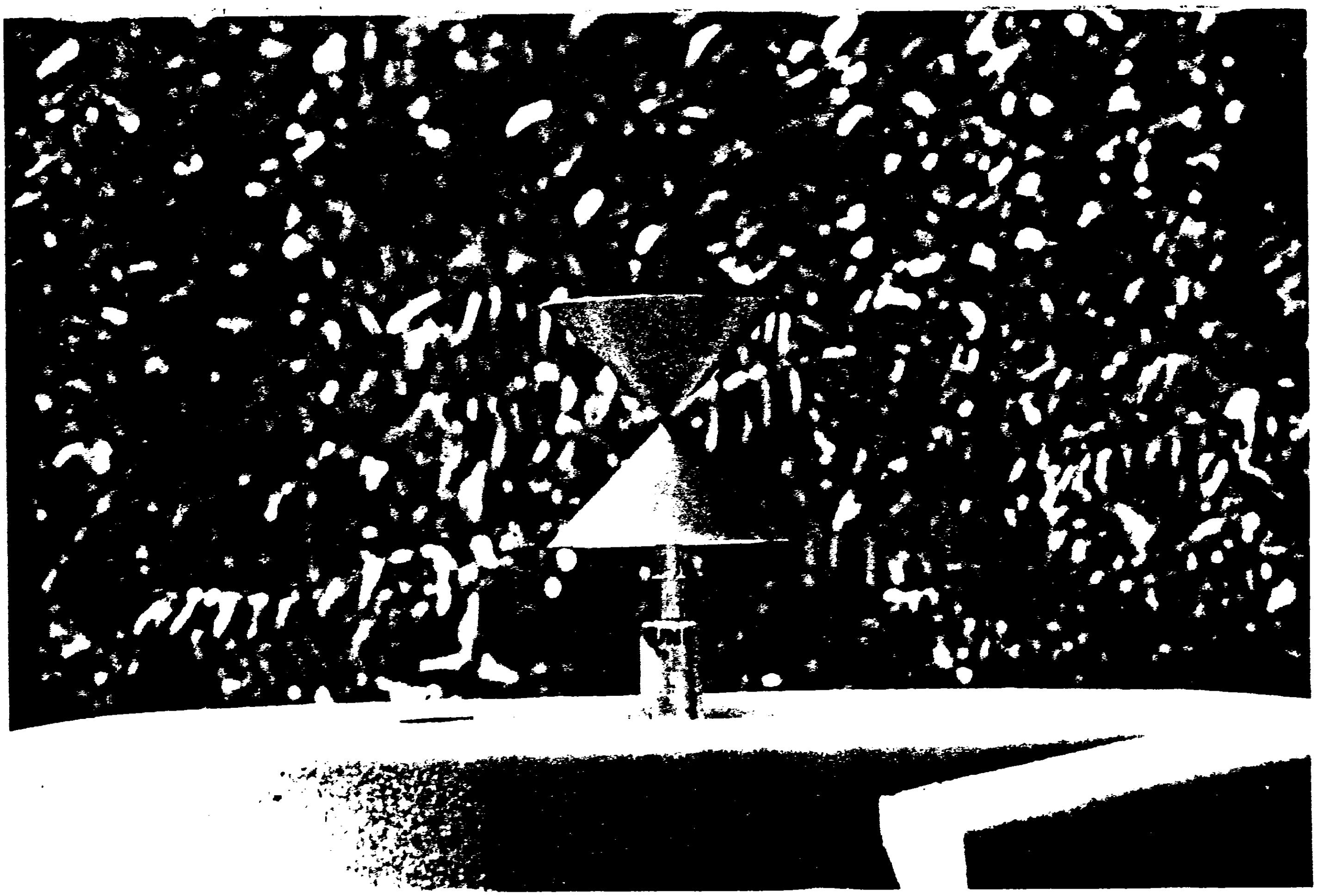
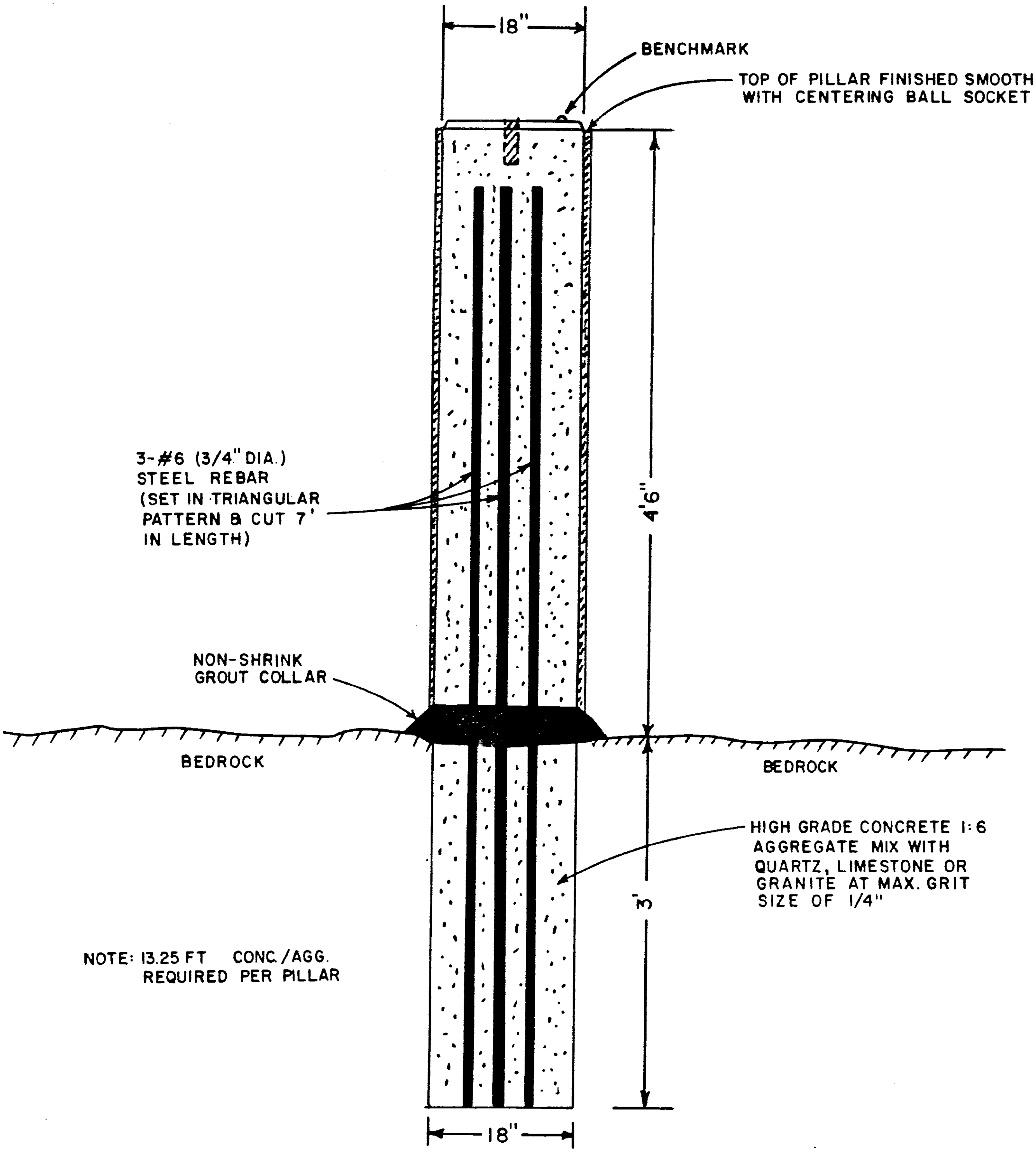
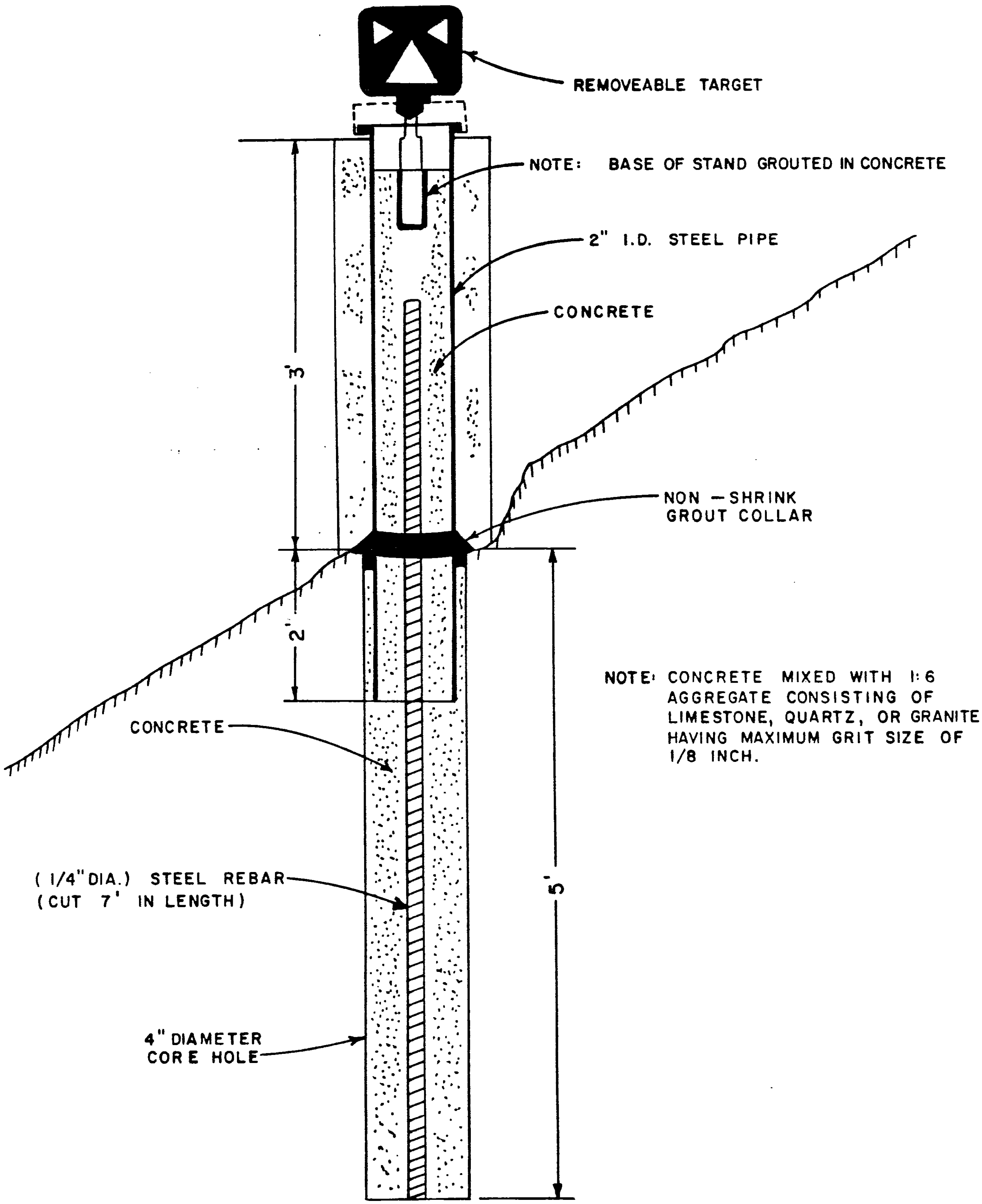


Figure 2.2 The UNB target design.



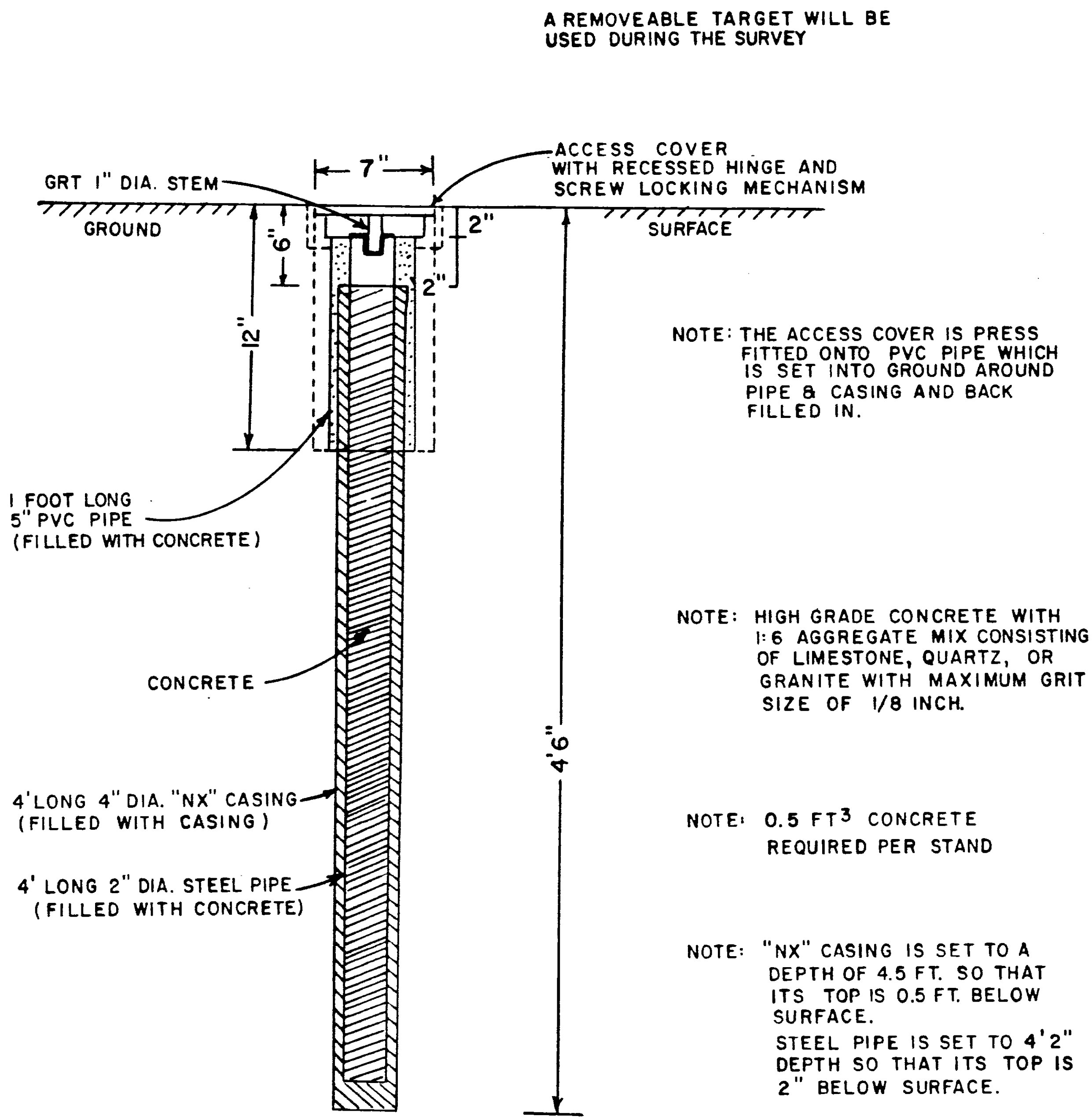
BSC	REFERENCE PILLAR DESIGN
PROJECT NO. 1-1654.00	
NOVEMBER, 1985	

Figure 2.3



BSC	SLOPE MONUMENT DESIGN
PROJECT NO. 1-1654.00	
NOVEMBER, 1985	

Figure 2.4



BSC	CREST MONUMENT DESIGN
PROJECT NO. 1-1654.00	
NOVEMBER, 1985	

Figure 2.5

3. OBSERVATION, ADJUSTMENT AND ANALYSIS

The dates of the three epochs are listed in Table 3.1 which also summarizes the prevailing weather conditions.

In the first two campaigns, Wild T2000 and DI4L instruments were used for the angle and distance measurements respectively. A Kern E2/DM502 combination was employed in the third campaign. The two electronic theodolites yielded comparable results and satisfied the specifications. However, the Kern E2 is more appropriate for this kind of work since it can provide precise vertical axis tilt measurements. The Kern DM502 proved to be slightly more precise than the Wild DI4L. This can be ascribed to the availability of high quality calibration data for the former instrument.

Observation data were recorded manually and reduced and checked in the evenings. The inability to perform real-time data validation and on-site station adjustments was a definite handicap. This problem is currently being addressed.

Temperature profile measurements were taken near the theodolite while the angular observations were being made at P3, P4 and P6. Several profiles from the first and second epochs have been analyzed (see Appendix IC). The results confirm the concern expressed in the pre-analysis regarding the severity of the refraction problem.

The horizontal and vertical network adjustments were performed in the office using the GNA software. The salient features of these computations are abstracted in the following sections.

3.1 THE HORIZONTAL NETWORK

The GNA results for the three campaigns may be found in Volume II of this report. The "Summary Reports" from each campaign are reproduced in Tables 3.2, 3.3 and 3.4.

In each case the standard deviation of unit weight corroborates the weighting scheme employed in the adjustment. The a priori standard deviation (0.6") used for the directions differs only slightly from the value (0.5") called for in the pre-analysis. In addition, the a priori distance standard deviations (+/- 3mm +/- 4.6 ppm for Epochs 1 and 2 and +/- 2mm +/- 3ppm for Epoch 3) are slightly better than the +/- 5mm +/- 5ppm specified in the pre-analysis.

The relative error ellipses (95% confidence level) indicate that all three epochs have satisfied the specification that the monitoring scheme be capable of detecting a 3mm horizontal movement at the 95% level of confidence.

3.2 THE VERTICAL NETWORK

The GNA results for the three vertical adjustments are contained in Volume II of this report. The "Summary Reports" for each campaign are reproduced in Tables 3.5, 3.6 and 3.7.

Once again the values of the standard deviation of unit weight confirm the a priori weighting scheme. In the first two epochs a standard deviation of 0.5" was used for weighting the zenith angles. A value of 0.6" was employed for the third adjustment.

The absolute 95% confidence intervals vary from 1.4 mm to 3.2 mm. Unfortunately, GNA did not provide the required relative confidence regions. However, reference to the LAD results (Volume III) reveals that the relative 95% confidence intervals for the inter-epoch comparisons varied from 1.7mm to 2.8mm. These results satisfy the specifications.

TABLE 3.1

Synopsis of the three campaigns

Epoch	Dates	Temperature °F	Weather Conditions
I	July 14	75 - 80	clear
	15	75 - 80	clear, gusting winds
	16	75 - 80	clear, haze
	17	-	-
	18	75 - 85	clear, calm
	19	65 - 75	overcast, windy
	20	65 - 75	light rain, windy
II	Sept 23	65	overcast, drizzle
	24	70	clear
	25	70	clear, windy in p.m.
	26	70	clear, calm
	27	70	clear
	28	60	overcast
III	Nov 18	40	overcast, calm
	19	20	clear, windy
	20	28	overcast, windy
	21	35	rain, windy
	22	28	clear, windy
	23	35	clear, light wind
	24	38	partly cloudy, windy

TABLE 3.2

Summary Report: Epoch 1 - horizontal

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	150	0.659136D+02	0.741045D+02	0.94312
AZIMUTHS	1	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	5	0.123737D+01	0.389550D+01	0.56360
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
HEIGHT DIFFERENCE	0	0.000000D+00	0.000000D+00	1.00000
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	156	0.671510D+02	78	0.92785

STATIONS:	FIXED	1
	FREE	32
	WEIGHTED	0
	TOTAL	33

CONVERGENCE:	ITERATIONS USED	3
	TOLERANCE	0.000100
	COMPUTATION TIME	38.830 SEC

TABLE 3.3

Summary Report: Epoch 2 - horizontal

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	139	0.836418D+02	0.690727D+02	1.10042
AZIMUTHS	1	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	4	0.210583D+01	0.292734D+01	0.84816
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
HEIGHT DIFFERENCE	0	0.000000D+00	0.000000D+00	1.00000
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	144	0.857477D+02	72	1.09130

STATIONS:	FIXED	1
	FREE	33
	WEIGHTED	0
	TOTAL	34

CONVERGENCE:	ITERATIONS USED	2
	TOLERANCE	0.000100
	COMPUTATION TIME	99.559 SEC

TABLE 3.4

Summary Report: Epoch 3 - horizontal

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	135	0.885519D+02	0.651182D+02	1.16613
AZIMUTHS	1	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	3	0.297731D+01	0.188182D+01	1.25783
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
HEIGHT DIFFERENCE	0	0.000000D+00	0.000000D+00	1.00000
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	139	0.915292D+02	67	1.16881

STATIONS:	FIXED	1
	FREE	33
	WEIGHTED	0
	TOTAL	34

CONVERGENCE:	ITERATIONS USED	2
	TOLERANCE	0.000100
	COMPUTATION TIME	100.453 SEC

TABLE 3.5

Summary Report: Epoch 1 - vertical

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	0	0.000000D+00	0.000000D+00	1.00000
AZIMUTHS	0	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	132	0.109791D+03	0.919897D+02	1.09248
HEIGHT DIFFERENCE	13	0.337395D+01	0.401033D+01	0.91723
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	145	0.113165D+03	96	1.08572

STATIONS:		
	FIXED	1
	FREE	48
	WEIGHTED	0
	TOTAL	49

CONVERGENCE:		
	ITERATIONS USED	2
	TOLERANCE	0.000100
	COMPUTATION TIME	14.328 SEC

TABLE 3.6

Summary Report: Epoch 2 - vertical

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	0	0.000000D+00	0.000000D+00	1.00000
AZIMUTHS	0	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	134	0.885879D+02	0.951584D+02	0.96486
HEIGHT DIFFERENCE	12	0.235715D-01	0.841642D+00	0.16735
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	146	0.886115D+02	96	0.96075

STATIONS:		
	FIXED	1
	FREE	50
	WEIGHTED	0
	TOTAL	51

CONVERGENCE:		
	ITERATIONS USED	2
	TOLERANCE	0.000100
	COMPUTATION TIME	151.313 SEC

TABLE 3.7

Summary Report: Epoch 3 - vertical

OBSERVATION TYPE	NUMBER	WEIGHTED SUM OF RESIDUALS SQUARED	REDUNDANCY	STD. DEV. OF UNIT WEIGHT
DIRECTIONS	0	0.000000D+00	0.000000D+00	1.00000
AZIMUTHS	0	0.000000D+00	0.000000D+00	1.00000
HORIZONTAL DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SLOPE DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
SCALED DISTANCE	0	0.000000D+00	0.000000D+00	1.00000
ZENITH DISTANCE	120	0.945190D+02	0.800372D+02	1.08671
HEIGHT DIFFERENCE	10	0.834129D+00	0.962835D+00	0.93077
OBSERVED COORDINATES	0	0.000000D+00	0.000000D+00	1.00000
COORDINATE DIFF.	0	0.000000D+00	0.000000D+00	1.00000
TOTAL	130	0.953531D+02	81	1.08499

STATIONS:	FIXED	1
	FREE	50
	WEIGHTED	0
	TOTAL	51

CONVERGENCE:	ITERATIONS USED	2
	TOLERANCE	0.000100
	COMPUTATION TIME	125.109 SEC

4. DEFORMATION ANALYSIS

4.1 HORIZONTAL ANALYSIS

4.1.2 EPOCH 1 vs. EPOCH 2

The results for this inter-epoch comparison may be found in Appendix III A. Plan #2 depicts the displacement vectors and their attendant 95% confidence ellipses.

The analysis of the reference stations reveals that point P2 is unstable. The displacement of 2.2mm is in a north-easterly direction. The remaining reference points - P1, P3, P4 and P5 - appear to be stable thereby providing a suitable base for the subsequent deformation analysis.

Five of the 27 object points have significant displacements. Two blocks of points were tested for group movement (Table 4.1). The first group containing 17 and 18, has significant X and Y displacements as well as a small significant rotation. The second group which includes all the object points has not moved significantly.

4.1.2 EPOCH 2 vs. EPOCH 3

The computations and analysis for this epoch comparison are contained in Appendix III B. The corresponding displacement vectors and their associated 95% confidence regions are presented on plan #3.

The stable base points are P1, P3, P4 and P5. Once again, the remaining reference point, P2, has been displaced in a north-easterly direction. In this instance, the movement of 3.5mm is somewhat more than the 2.2 mm incurred in the Epoch 1/Epoch 2 interval. The tower (1218) has undergone a significant displacement of 7.1mm in a westerly direction.

Nine (one third) of the object points have been displaced by significant amounts. All of these have a downstream (easterly) component. Inspection of Plan#3 reveals that all but two of the 27 displacement vectors have a downstream component.

There are three fairly clear groupings of points: (1) 32, 33, 34, 35; (2) 17, 18 and (3) 38, 39. Each of these was tested for significant group movement. The results are summarized in Table 4.2. All three have significant X-coordinate (downstream) components. In addition, Group #1 has a significant Y-coordinate (northerly) component. None of the blocks manifests a significant rotation. A fourth group containing all 27 object points was examined. In this case, no translation seems to have occurred although the group does exhibit a very small rotation.

4.1.3 EPOCH 1 vs. EPOCH 3

The results for this comparison may be found in Appendix IIIC. The displacement vectors and their associated 95% confidence ellipses are shown on Plan #4. Spanning, as it does, the full July 1986 - November 1986 interval, this inter-epoch analysis yields results which may be viewed as a composite of the previous two analyses (see Sections 4.1.1 and 4.1.2).

Not unexpectedly, P2 manifests a large north-easterly displacement of 5.6mm. The remaining reference points - P1, P3, P4 and P5 - do not have significant displacements. Accordingly, they are used as the base for the ensuing deformation analysis.

Ten of the 27 object points appear to have incurred significant displacements. All of these have a downstream component. Indeed, only one (11) of the object points does not exhibit a downstream trend.

Two blocks of points have been tested for significant group movement. (refer to Table 4.3). The first group, containing points 32, 33, 34, 35 and 36, has a relatively large downstream (X displacement) component and a somewhat smaller northerly (Y displacement) component. For a block of such small size, the rotation is negligible. The second group (points 22, 23 and 24) also has significant X (downstream) and Y (northerly) translations. The attempt to model the combined movement of all object points does not reveal significant coordinate translations. Although it is statistically significant, the rotation is very small for a block of this extent. Moreover, it is doubtful whether a rotation has any real physical meaning for a non-rigid body such as this.

4.1.4 SUMMARY

It is apparent from the foregoing analysis that most of the deformation activity seems to have occurred in the second inter-epoch interval., i.e., between the September 1986 and November 1986 campaigns. In summary, the following comments may be made with regard to the horizontal deformation analysis:

1. Downstream movement of "several millimetres" (1mm - 4mm) is manifest in the upper part of line A. This extends from the crest center-line (point 32) down to points 35 and 36 which lie on the bulge.

2. Downstream movement of "several millimetres" (1mm - 4mm) seems to have occurred in the upper part of line B. This deformation is limited primarily to the immediate neighborhood of the downstream crest edge, i.e., to the vicinity of points 22, 23 and 24.

3. Points 17 and 18 have undergone significant movements of approximately 2mm-4mm. However, there is no clear directional trend as is evident when examining the vector orientations shown on Plans #2 and #3.

4. Some downstream displacement is evident below the bulge in line A (points 38 and 39).

5. There seems to be a general downstream trend throughout the set of object points. At present, this "movement" is less than the sensitivity of the monitoring scheme and is not significant at the 95% level of confidence. There is a possibility that this trend is caused by changes in lateral refraction from one campaign to the next.

6. Except for the large north-easterly displacement of point P2, the reference network is stable. The movement of P2 may be ascribed to geological factors (e.g., deformation of the exposed bedrock) or to distortion of the pillar (e.g., concrete shrinkage). An on-site inspection may provide clarification.

TABLE 4.1

Epoch 1 versus Epoch 2

Summary of the group movement analyses - horizontal
(Refer to Appendix III A)

Group #	1	2
Stations	17 (3.0) 18 (3.6)	All Object Points
X displacement[1]	-1.0mm	NO
Y displacement[2]	3.8mm	NO
Rotation[3]	-11 arc seconds	NO

1. Positive to the east (downstream)
2. Positive to the north
3. Positive clockwise from north
4. Displacement vectors in mm.

TABLE 4.2

Epoch 2 versus Epoch 3:

Summary of the group movement analyses.
(Refer to Appendix IIIB)

Group #	1	2	3	4
Stations	32(2.9)[4] 33(3.7) 34(2.6) 35(2.1)	17(2.7) 18(3.7)	38(1.7) 39(2.6)	All Object Points
X displacement[1]	2.1mm	1.7mm	1.9mm	NO
Y displacement[2]	1.1mm	NO	NO	NO
Rotation[3]	NO	NO	NO	-1 arc second

1. Positive to the east (downstream)
2. Positive to the north
3. Positive clockwise from north
4. Displacement vectors in mm

TABLE 4.3

Epoch 1 versus Epoch 3

Summary of the group movement analyses - horizontal
(Refer to Appendix III C)

Group #	1	2	3
Stations	32 (3.7)[4] 33 (3.4) 34 (2.1) 35 (2.2) 36 (1.4)	22 (1.7) 23 (3.9) 24 (2.0)	All Object Points
X displacement[1]	3.0mm	1.1mm	NO
Y displacement[2]	2.3mm	1.9mm	NO
Rotation[3]	+6 arc seconds	NO	-1 arc second

1. Positive to the east (downstream)
2. Positive to the north
3. Positive clockwise from north
4. Displacement vectors in mm

4.2 VERTICAL ANALYSIS

4.2.1 EPOCH 1 vs. EPOCH 2

The results for this comparison may be found in Appendix IIID. Plan #5 shows the displacement vectors.

All five reference points (P1 through P5) pass the stability test at the 95% level of confidence. They form a suitable base for the subsequent deformation analysis.

All but two of the 27 object points have negative displacement vectors (Table 4.4). This indicates an apparent downward movement of the points in the Epoch 1 - Epoch 2 interval. The vectors are small, varying in length from 0.02mm to 2.3mm with a mean of 0.9mm. The analysis reveals that none of these displacements is significant at the 95% level of confidence.

4.2.2 EPOCH 2 vs EPOCH 3

The results for this analysis are included in Appendix IIIE. The corresponding displacement vectors are shown on Plan #6.

Examination of the base points (P1 through P5) indicates that there is no significant movement of the reference network.

All the object points appear to have undergone substantial positive (upward) vertical displacements (Table 4.4). The movements vary from 0.2mm to 6.2mm with a mean value of 2.7mm. Twenty one (78%) of the 27 displacements are significant. An attempt was made to model the object point movement. Considered together as a single group, the 27 points have a positive translation of 4.3mm.

4.2.3 EPOCH 1 vs. EPOCH 3

The results for this comparison may be found in Appendix IIIF. Plan #7 shows the displacement vectors. Once again, this epoch comparison should be viewed as a composite of the previous two analyses (see Sections 4.2.1 and 4.2.2).

The stable point analysis reveals no significant movement of the reference points. All 27 object points manifest positive (upward) displacements which vary from 0.2mm to 4.3mm with a mean of 1.9mm (Table 4.4). Eleven (41%) displacements are significant. The group analysis, which includes all object points, reveals a positive (upward) translation of 3.4mm.

4.2.4 SUMMARY

The inter-epoch comparisons reveal very obvious trends in the displacement vectors (Table 4.4). These may be explained by the effect of changes in the coefficient of refraction from one campaign to the next. This problem is addressed in some depth in Appendix IC. At present - considering the 4 month interval between Epochs 1 and 3 - the expected size of the point displacements is of the same order of magnitude as the systematic refraction error. Therefore, it is not possible to discriminate between real vertical movements and the apparent displacements caused by refraction.

Owing to the fact that the rays linking the reference stations have ample ground clearances, they are less affected by changes in refraction than are the rays between the reference and object points which generally graze close to the surface. This is borne out by the results of the base point analyses which reveal that all five reference stations have remained stable at the 95% level of confidence.

TABLE 4.4

Single Point Displacements
(vertical network analysis)

Point	Epoch 1 to Epoch 2	Epoch 2 to Epoch 3	Epoch 1 to Epoch 3
P1	-1.5	0.6	-0.9
P2	0.3	0.06	0.4
P3	1.6	-1.0	0.5
P4	-0.8	-0.9	-1.6
P5	0.4	1.2	1.6
P6	-0.8	0.2	-0.6
31	0.02	3.5*	3.6*
32	-0.7	3.4*	2.7*
33	-1.0	2.0*	1.0
34	-1.1	2.0*	0.9
35	-0.3	1.4	1.1
36	-0.7	1.6	0.8
37	-0.3	3.1*	2.8
38	-0.8	3.2*	2.4
39	-2.3	2.7*	3.4*
21	-0.4	2.9*	2.5*
22	-0.4	3.3*	2.9*
23	-0.9	3.0*	2.1
24	-0.7	1.7	1.0
25	-1.5	2.9*	1.4
26	-0.8	4.7*	3.9*
27	-0.3	2.5	2.1*
28	-0.9	1.8	0.9
29	-1.9	6.2*	4.3*
11	-1.5	3.4*	1.9
12	-0.4	3.7*	3.2*
13	-0.7	2.6*	1.9
14	-1.4	1.6	0.2
15	-1.4	2.3*	0.9
16	-0.6	2.0*	1.4
17	0.06	2.3*	2.4*
18	-1.6	2.7*	1.1
19	-1.6	2.9*	1.3

* - Displacement is significant at the 95% level of confidence (significance level = 0.05)

5. CONCLUSIONS

In general, the outcome has confirmed the relevance of the pre-analysis. The horizontal deformation results are pleasing. The vertical analysis has suffered from the adverse influence of atmospheric refraction. Since the refraction errors vary depending on the vertical air temperature gradients, spurious vertical displacements of as much as 5mm may occur when comparing data from winter and summer campaigns. Estimates for the refraction errors may be obtained by measuring vertical temperature gradients and/or by running a few selected lines of precise geometric leveling (See Appendix IC). However, for several reasons, this problem may not be all that intractable:

- The refraction error may be expected to be similar for campaigns having similar prevailing temperature conditions. For example, the July 1986 vs July 1987 comparison should be largely free from the influence of refraction.

- Over longer time periods the point displacements may be significantly greater than the average magnitude of the refraction error.

The analysis has shown that some deformation is evident in the structure, particularly along the crest edge near the spillway. This may be confirmed by the analysis of the slope inclinometer data and by the remaining campaigns of the geodetic monitoring program. The results from the first three epochs have shown that geodetic techniques are well suited to monitoring programs of this kind.

6. BIBLIOGRAPHY

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APPENDIX IA

Summary of
Daily Activities

The following tabulations have been abstracted from Boston Survey Consultants' "Daily Chief Reports":

IA.1 Epoch 1

DATE	WEATHER	ACTIVITY
7/14/86	clear 75°F - 80°F	travel to site, cut lines wrapped pillars, set targets
7/15/86	clear, windy, 75°F - 80°F	direction obs. at P1,P4 and P5
7/16/86	clear, hazy, 75°F - 80°F	direction obs at P4 distance obs P6 to P1,P2,P4 and P5
7/17/86	-----	direction obs at P3
7/18/86	clear, 75°F - 85°F	direction obs at P2
7/19/86	overcast, windy, 65°F - 75°F	direction obs at P6
7/20/86	windy, light rain 65°F - 75°F	repeated some dir obs at P3 repeated some dir obs at P6 measured distance P6-P3 travel to Boston.

IA.2 Epoch 2

DATE	WEATHER	ACTIVITY
9/23/86	overcast, light rain, 65°F	travel to site, site preparation, install PVC sleeves, install bench marks on two pillars
9/24/86	fog in a.m. clear p.m. 70°F	install two pillar bench marks install water target (1218), paint PVC tubes, direction obs at P6
9/25/86	clear, calm a.m. wind in p.m. 70°F	install one pillar bench mark, direction obs at P1, direction obs at P2
9/26/86	clear,calm 70°F	direction obs. at P3 and P5, calibrated NA2 level
9/27/86	clear 70°F	direction obs. at P4, repeated dir obs at P6
9/28/86	overcast, 60°F	distance measurements P4 to P1,P2, P3 and P5, some additional dir obs at P6, level from NGVD disc to P1, winterize crest and pillar monuments, clean up site, travel to Boston

IA.3 Epoch 3

DATE	WEATHER	ACTIVITY
11/18/86	overcast -5°C	travel to site, direction obs. at P1 and P5, set out crest targets and tripod at P6.
11/19/86	windy -6°C	prepared all pillars, P6 and slope monuments, dir obs from P4
11/20/86	overcast, windy -2°C	direction obs. at P6 and P3
11/21/86	rain, snow, wind 2°C	no field work owing to severe weather conditions, some data reductions done.
11/22/86	clear,windy -2°C	direction obs at P3 and P2
11/23/86	clear,windy 3°C	direction obs. at P2 and P5, distance measurements P4, to P1, P3, P5, P6.
11/24/86	fog, windy 3°C	direction obs. at P6, distance measurements P6 to P1,P2, travel to Boston

APPENDIX IB

Report No. 1
Page 1 of 2

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: July 14, 1986
Time: 08:00 hours

Safety meeting was held this date for the following BSC Group personnel:

Clark R. Donkin
Mark W. Rohde
L. Jeff Lowell

Conducted by: Kevin Hanley

Subjects discussed included:

Accident Prevention
Individual Protective Equipment
Prevention of Falls

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: July 14, 1986
Time: 08:00 hours

Total on-site exposure hours for BSC Group personnel:

July 14, through July 20, 1986:

Clark R. Donkin	81.0 manhours
Mark W. Rohde	81.0 manhours
L. Jeff Lowell	81.0 manhours

Signature: Kevin Hanley
The BSC Group / Division Manager

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: August 25, 1986
Time: 11:00 hours

Safety meeting was held this date for the following BSC Group personnel:

Clark R. Donkin
Mark W. Rohde
L. Jeff Lowell
W.J. Trevor Greening

Conducted by: Kevin Hanley

Subjects discussed included:

Accident Prevention
Individual Protective Equipment
Prevention of Falls

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: August 25, 1986
Time: 11:00 hours

Total on-site exposure hours for BSC Group personnel:

<u>September 23, through September 28, 1986:</u>

Clark R. Donkin	53.0 manhours
Mark W. Rohde	53.0 manhours
L. Jeff Lowell	53.0 manhours
W.J. Trevor Greening	32.5 manhours
Kevin Hanley	5.0 manhours

Signature: Kevin Hanley
The BSC Group / Division Manager

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: November 18, 1986
Time: 08:30 hours

Safety meeting was held this date for the following BSC Group personnel:

Clark R. Donkin
Mark W. Rohde
L. Jeff Lowell
W.J. Trevor Greening

Conducted by: Kevin Hanley

Subjects discussed included:

Accident Prevention
Individual Protective Equipment
Prevention of Falls

THE BSC GROUP

SAFETY MEETING AT
BALL MOUNTAIN DAM

TO: Safety Office, NED
FROM: Division Manager

Date Held: November 18, 1986
Time: 08:30 hours

Total on-site exposure hours for BSC Group personnel:

July 14, through July 20, 1986:

Clark R. Donkin	52.0 manhours
Mark W. Rohde	52.0 manhours
L. Jeff Lowell	26.5 manhours
W.J. Trevor Greening	26.5 manhours

Signature: Kevin Hanley
The BSC Group / Division Manager

APPENDIX IC

Ball Mountain Dam
An Assessment of the Effects of Atmospheric Refraction

INTRODUCTION

In the Preanalysis of the monitoring survey it was pointed out that changes in the coefficient of refraction may adversely affect the results of the trigonometric levelling at Ball Mountain Dam. It was suggested that the problem might be ameliorated by measuring vertical temperature gradients/profiles during each campaign. Accordingly, several trial profile measurements were undertaken during the July 1986 and September 1986 epochs. A preliminary analysis of these data indicates that the influence of refraction requires further and continued attention.

THEORETICAL BACKGROUND

Kukkamaki (1938, 1939a, 1939b) proposed that vertical temperature gradients and hence refraction corrections could be estimated from observed vertical temperature profiles by means of a simple mathematical model:

$$T = a + bh^{c} \qquad (1)$$

where a, b and c are constants for a particular profile. T is the mean temperature at height h above the ground. By measuring several (at least 3) temperatures at different heights it is possible to solve for the values of a, b and c. If redundant measurements are made then estimates can be obtained using a least squares adjustment.

The mean vertical temperature gradient is obtained by differentiation of equation (1):

$$\frac{dT}{dh} = bch^{c-1} \qquad (2)$$

In accordance with the free convection theory, many authors (e.g. Fraser, 1977; Holdahl, 1982) set $c = -1/3$. This assumption is valid during typical unstable daytime conditions.

The coefficient of refraction may be computed using the expression (see e.g., Greening, 1985):

$$k = 78.83 \frac{PR}{T^2} [0.0342 + \frac{dT}{dh}] 10^{-6} \qquad (3)$$

where P is the atmospheric pressure [mb],
R is the radius of curvature of the earth [m], and
T is the mean atmospheric temperature [K].

In equation (3), the gradient dT/dh is the dominant term. The value of k is rather insensitive to assumptions made with regard to the atmospheric pressure (P) and temperature (T).

Finally, the total refraction error in a particular sighting can be evaluated by numerical integration along the optical path (Angus-Leppan, 1971; 1979):

$$\begin{aligned} Ref = \frac{1}{R} \{ & \frac{s_1}{2} (k^1 \; S + k_2 \; [S-s_1]) \\ & + \frac{s_2}{2} (k_2 \; [S-s_1] + k_3 \; [S-s_1-s_2]) \\ & + \ldots\ldots + \frac{sn}{2} (k_n \; [S-s_1-\ldots\ldots-s_n \; -_1\} + 0)\} \end{aligned} \qquad (4)$$

R is the radius of curvature of the earth, s_1, s_2, ..., s_n are successive subsections of the total distance S and k_1, k_2, ..., k_n are the corresponding coefficients of refraction.

The use of equation (4) pre-supposes a fairly detailed knowledge of the terrain profile and temperature stratification along the line of sight. In the following section, equations (1) through (4) are employed to evaluate the significance of the refraction error in the heighting of one of the object points on the dam wall. These computations have been made to assess the seriousness of the refraction phenomenon. They are not intended for the application of corrections.

RESULTS

Table 1 shows the temperature measurements for four profiles taken from the July and September campaigns. For each data set, a least squares adjustment provided estimates of the coefficients a and b (Table 2). the value of c = -1/3 was held fixed. Graphs of the computed profiles appear in Figure 1 through 4. Equations (2) and (3) were used for computing the vertical temperature gradients and corresponding values of k (Figures 5 through 8).

When $dT/dh < 0.0342\ Cm^{-1}$, then $k < 0$ and the curvature of the optical path is convex to the ground. In this case the object points will appear to be lower than their true positions (Figure 11). If $dT/dh > 0.0342\ Cm^{-1}$, then $k > 0$ and points will appear higher than their true locations. The former situation can be expected to occur during typical warm summer days when the heat flux is upward out of the ground. In winter months and/or at night the latter may occur.

In order to assess the problem, refraction errors were computed for the height differences P3-28 and P6-28. Figure 9 shows the horizontal positions of these stations. The terrain profiles are presented in Figure 10 and the refraction error computations are summarized in Table 3.

It is somewhat surprising that the computed refraction errors agree so well. In general, variations of "several millimetres" may be expected to occur. However, the outcome does emphasize the systematic nature of the phenomenon. During any particular campaign, a trend may occur throughout the set of object points. Unfortunately this systematic effect may change seasonally. For example, in summertime, when strong negative temperature gradients predominate, the average refraction error may lie in the range -10mm to -3mm. On the other hand, during winter the near surface gradients may be positive in which case the refraction error is positive. This seasonal variation would be manifest as an apparent upward movement of the object points from summer to winter. The opposite would occur in the winter - summer interval.

CONCLUSIONS AND RECOMMENDATIONS

It is clear that the refraction problem requires further attention. If the effect is ignored, it may be extremely difficult to discriminate between spurious refraction induced displacements and the real vertical motions of the object points.

The following recommendations are made:

1. The process of collecting vertical temperature profile information should be fully implemented.

2. Resources should be allocated to the analysis of the temperature data.

3. Resources should be made available for precise geometric levelling between certain network points as a means of verifying the systematic refraction error component.

With regard to recommendation 3 above, it is suggested that the following loop be measured: P4 - 31 - 21 - 11 - P6 - 15 - 25 - 35 - P4. This will entail the observation, under very difficult conditions, of approximately 35-40 setups. The levelling would require one extra field day per epoch while the analysis of the temperature profile and levelling data will necessitate a further 4 days' office work.

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TABLE 1
SUMMARY OF TEMPERATURE
PROFILE MEASUREMENTS

#	DATE	TIME	A	B	C	D	E	F	REMARKS
1	1986 - 0715	13:00	22.5	22.8	23.5	24.5	25.1	26.0	middle of crest, clear, sunny, 15 mph winds, P1 and P5 occupied
2	1986 - 0717	11:30	24.7	25.6	25.4	26.2	26.2	26.2	P3 occupied gradients in bush clowdy / calm
3	1986 - 0727	11:30	15.2	16.9	16.8	18.7	20.8	21.0	P3 occupied, clowdy / calm
4	1986 - 0924	14:00	22.1	22.5	22.9	23.2	24.4	25.2	P6 occupied, Sunny / calm

PROBE HEIGHTS

A	4.0
B	3.0
C	2.0
D	1.2
E	0.6
F	0.3

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TABLE 2

SUMMARY

LEAST SQUARES SOLUTION FOR COEFFICIENTS
OF THE TEMPERATURE PROFILE

		1	2	3	4
	a	20.188	24.739	11.829	19.968
	b	4.057	0.935	6.697	3.571
		1.30	2.10	3.52	0.61
		1.772	2.85	4.79	0.83
		1.767	2.84	4.78	0.83
		-0.95	-0.95	-0.95	-0.95
RESIDUALS:					
	V	0.24	0.63	0.85	0.12
	V	0.20	-0.21	-0.43	-0.06
	V	-0.09	0.08	0.34	-0.10
	V	-0.50	-0.58	-0.57	0.13
	V	-0.10	-0.35	-1.03	-0.20
	V	0.25	0.44	0.83	0.10

TABLE 3

SUMMARY OF REFRACTION ERROR COMPUTATIONS

LINE P3 - B8

SEGMENT #	1	2	3	4	
SEGMENT LENGTH	50m	47	33	32	
ACCUMULATED DISTANCE	50m	97	130	162	
RAY CLEARANCE	1.8m	11.5	22.3	11.0	from figure
POINT VALUE OF k	-5.8	-0.3	-0.01	-0.3	from figure
REFRACTION ERROR	-3.82mm	-0.13	-0.03	-0.02	

TOTAL: -4.0mm

LINE P6 - B8

SEGMENT #	1	2	3	4	
SEGMENT LENGTH	35m	35	35	36	
ACCUMULATED DISTANCE	35	70	105	141	
RAY CLEARANCE	1.5m	2.1	2.7	1.8	from figure
POINT OF VALUE OF k	-3.8	-2.3	-1.6	-2.9	from figure
REFRACTION ERROR	-2.14mm	-0.98	-0.60	-0.29	

TOTAL: -4.0mm

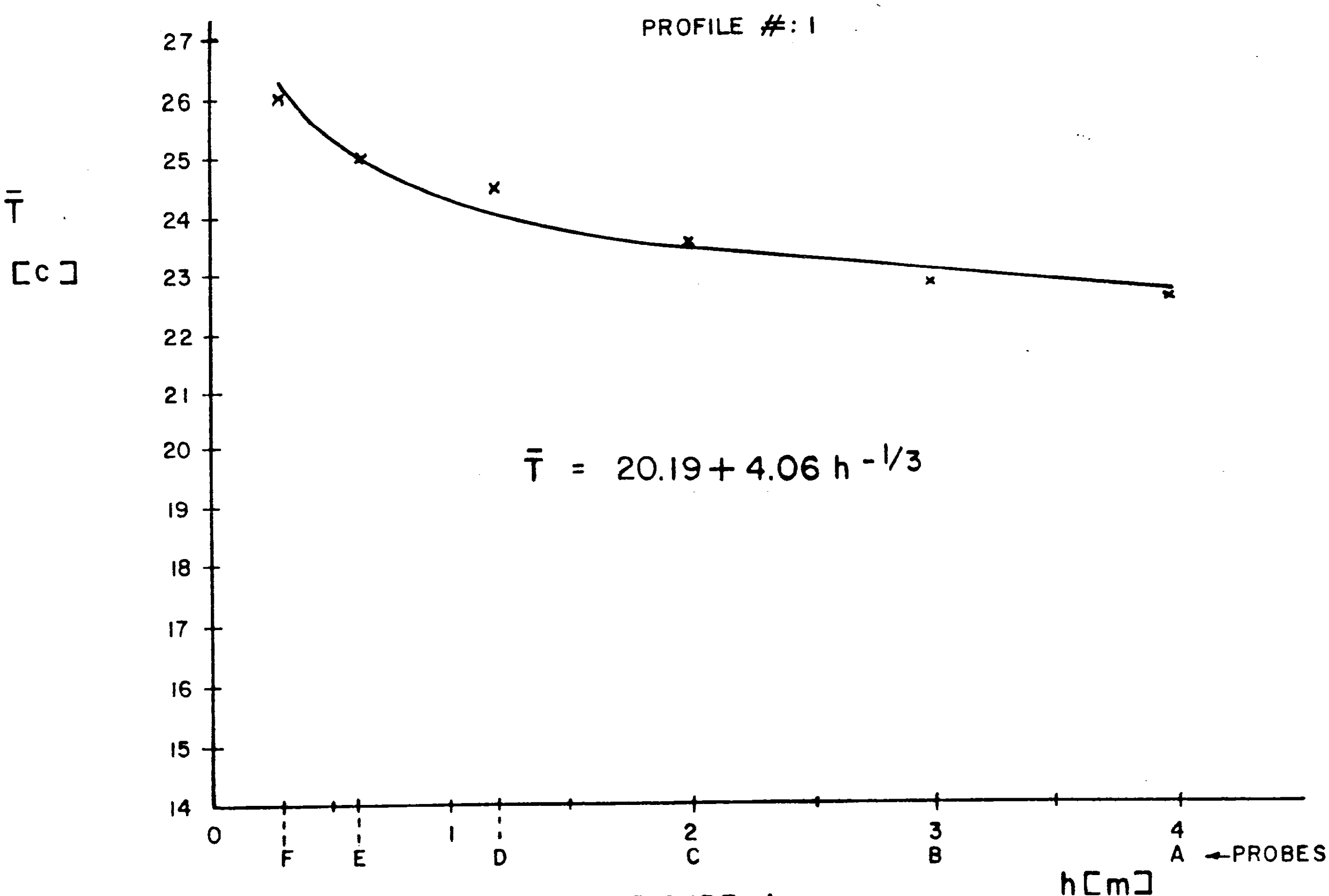


FIGURE 1

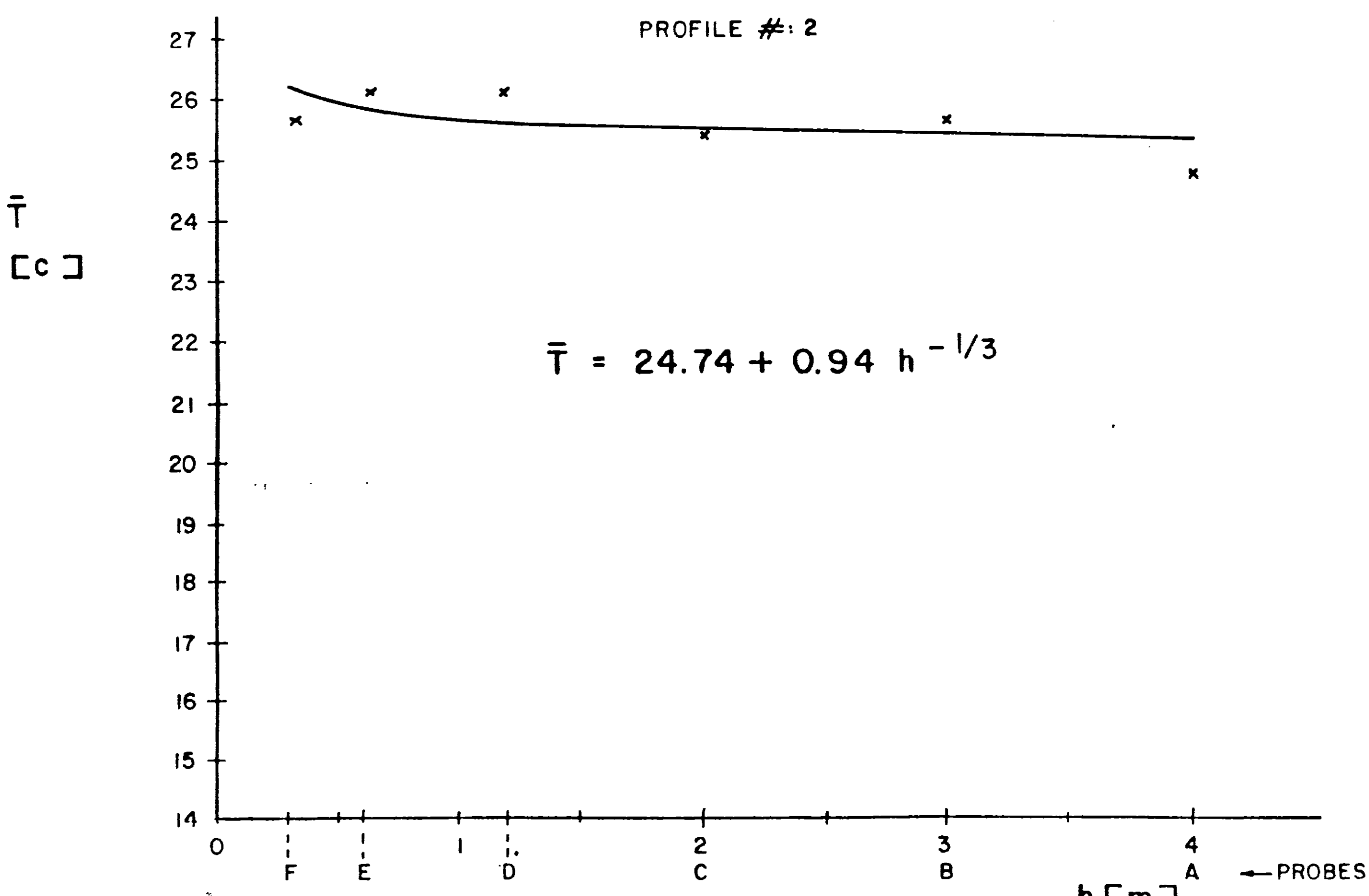


FIGURE 2

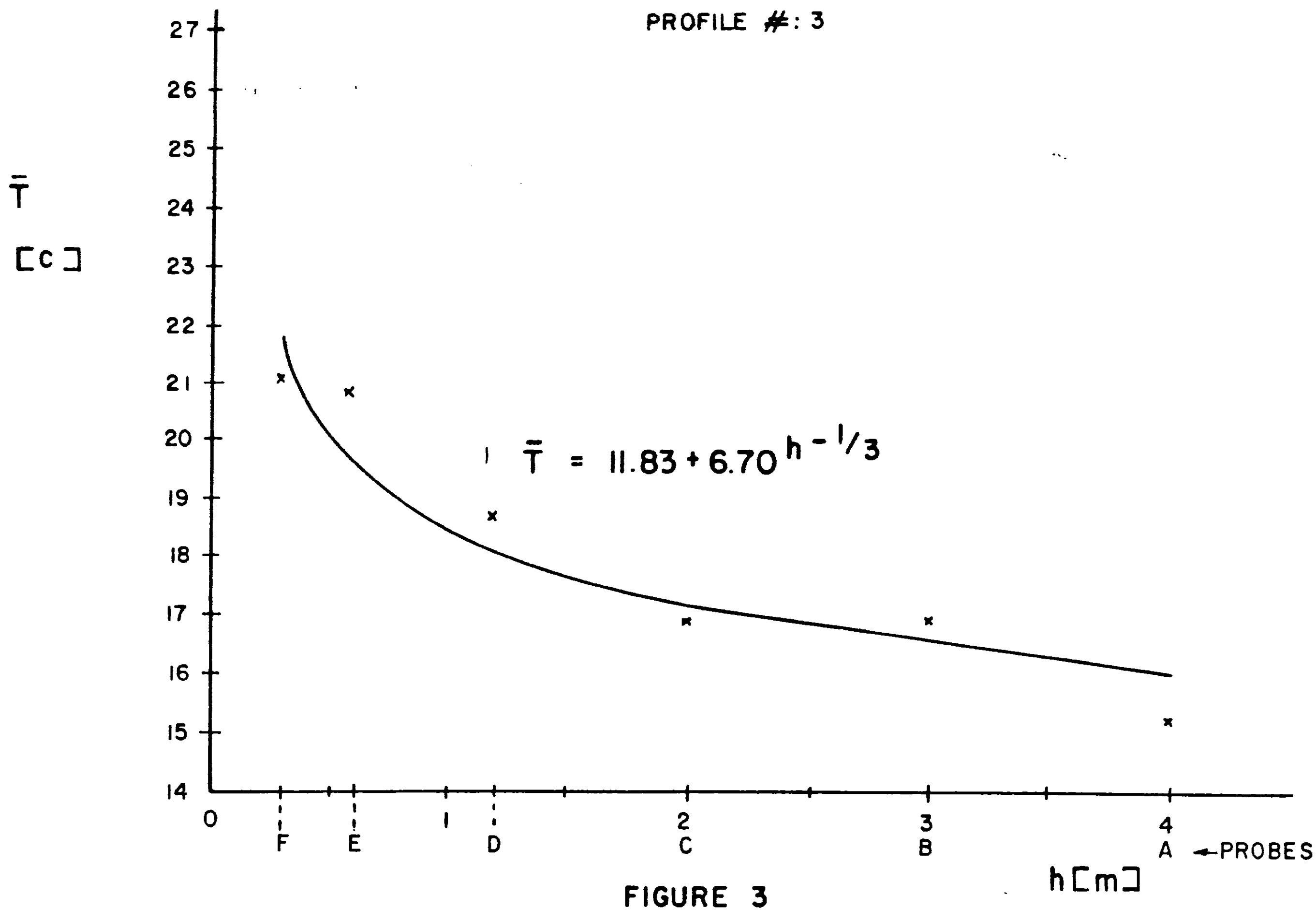


FIGURE 3

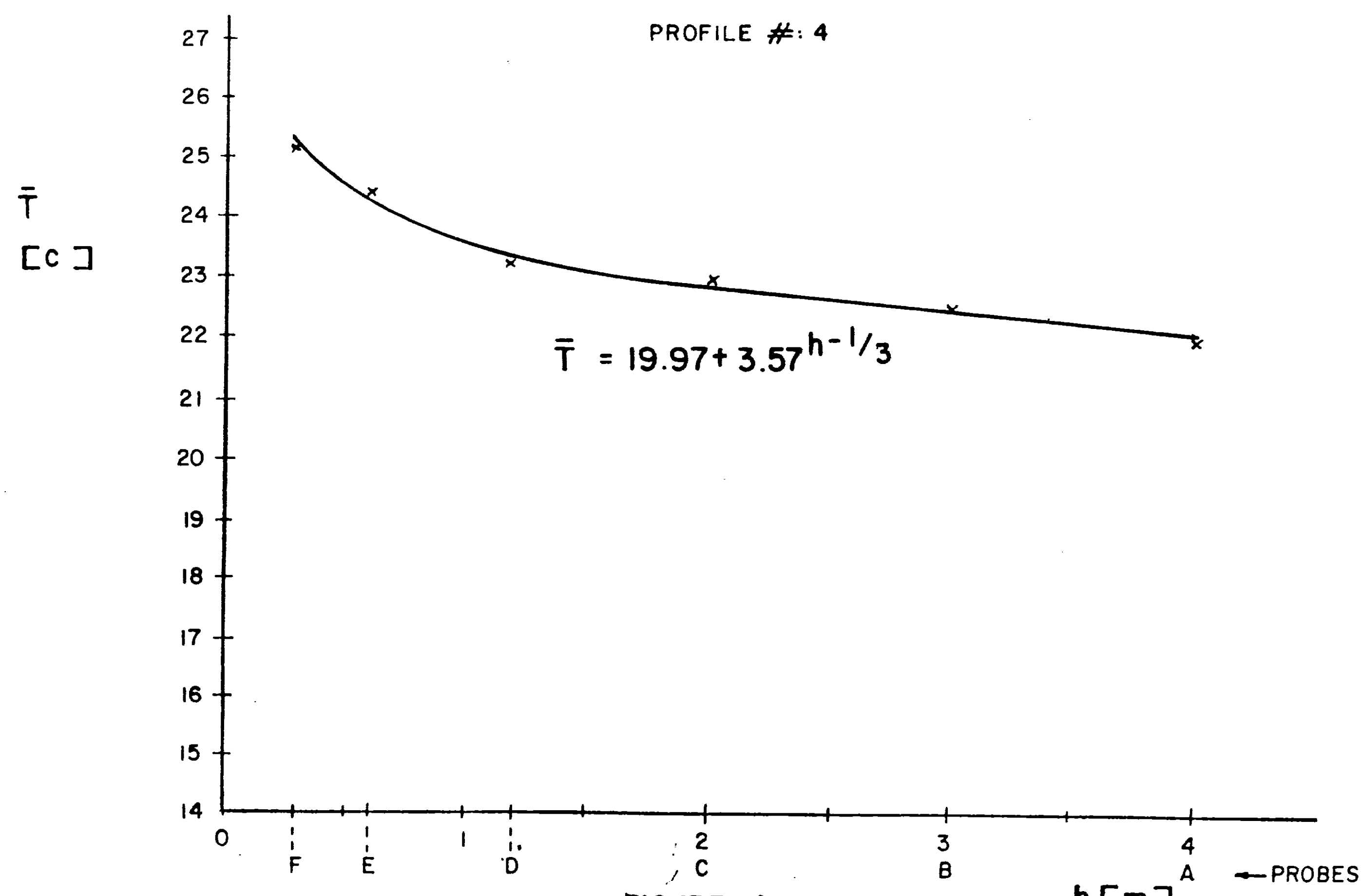


FIGURE 4

PROFILE # : 1

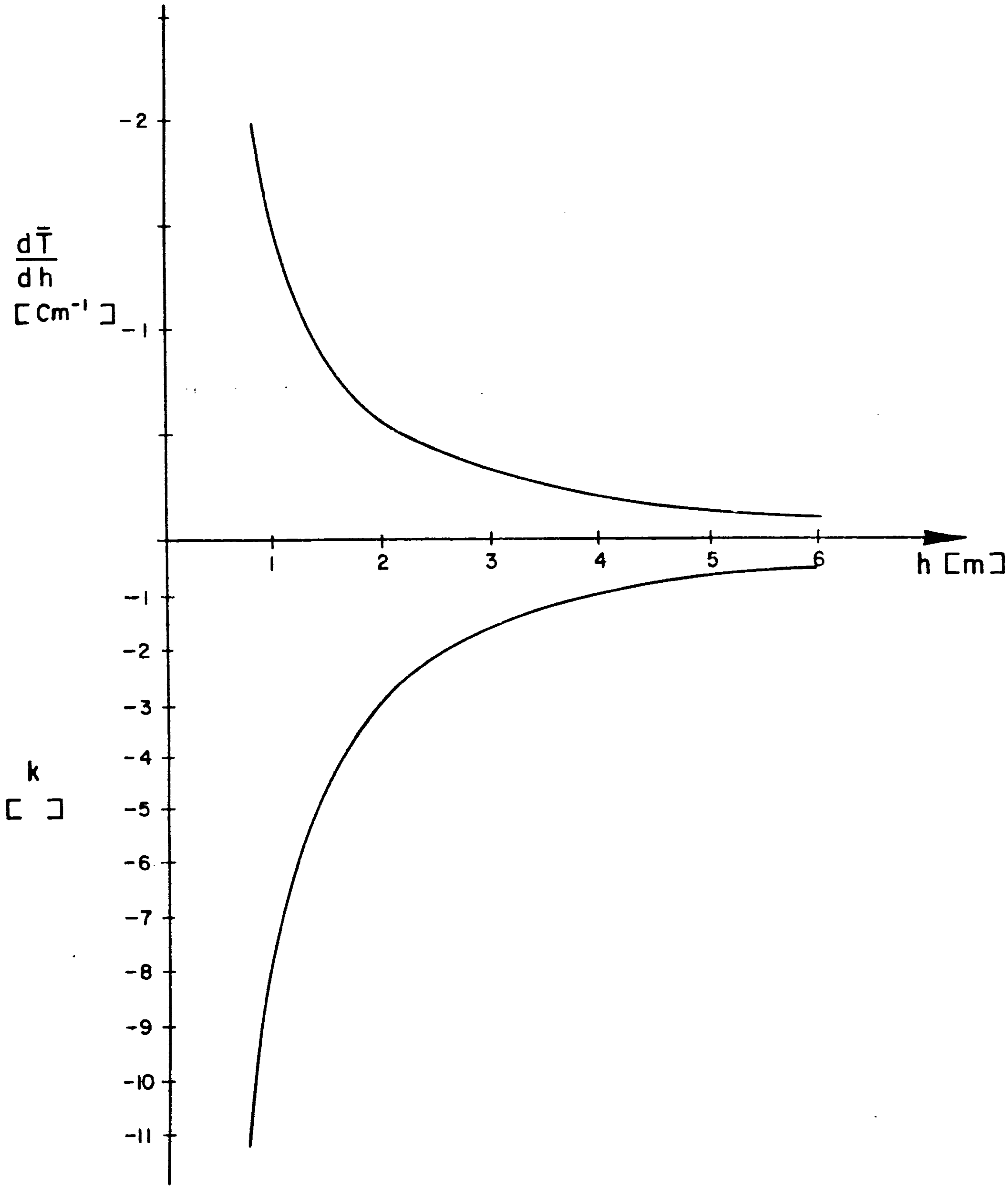


FIGURE 5

PROFILE #: 2

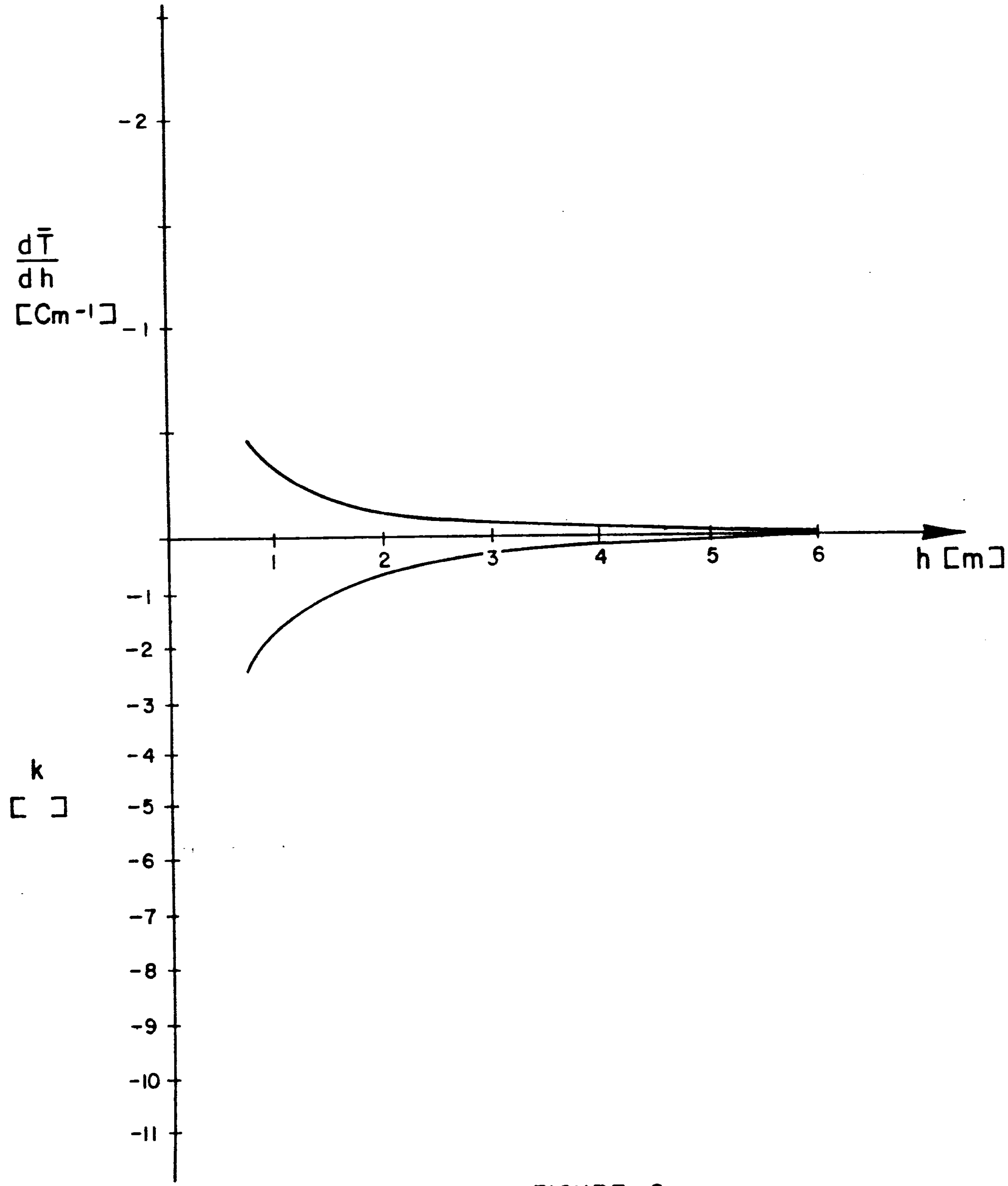


FIGURE 6

PROFILE #: 3

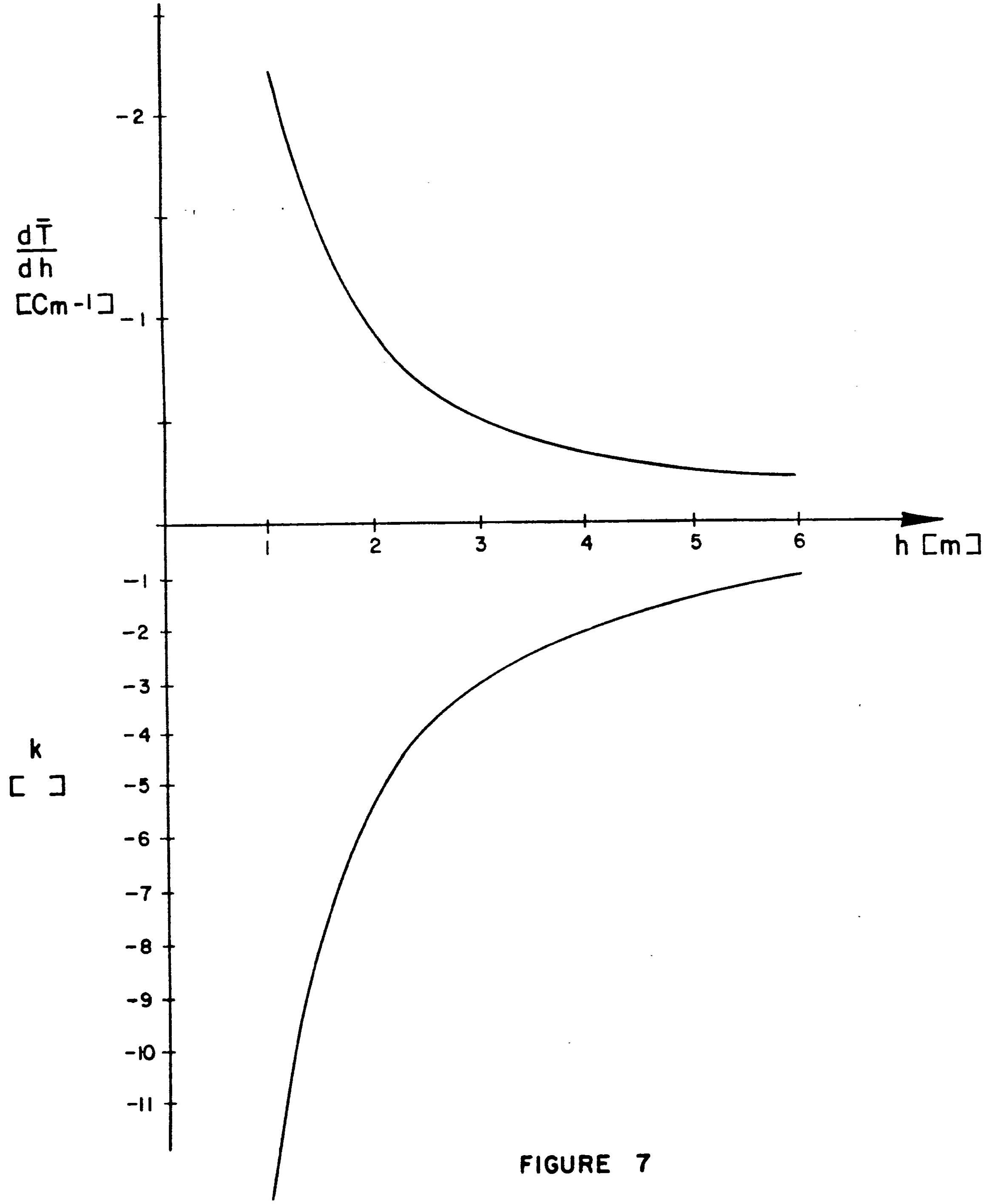


FIGURE 7

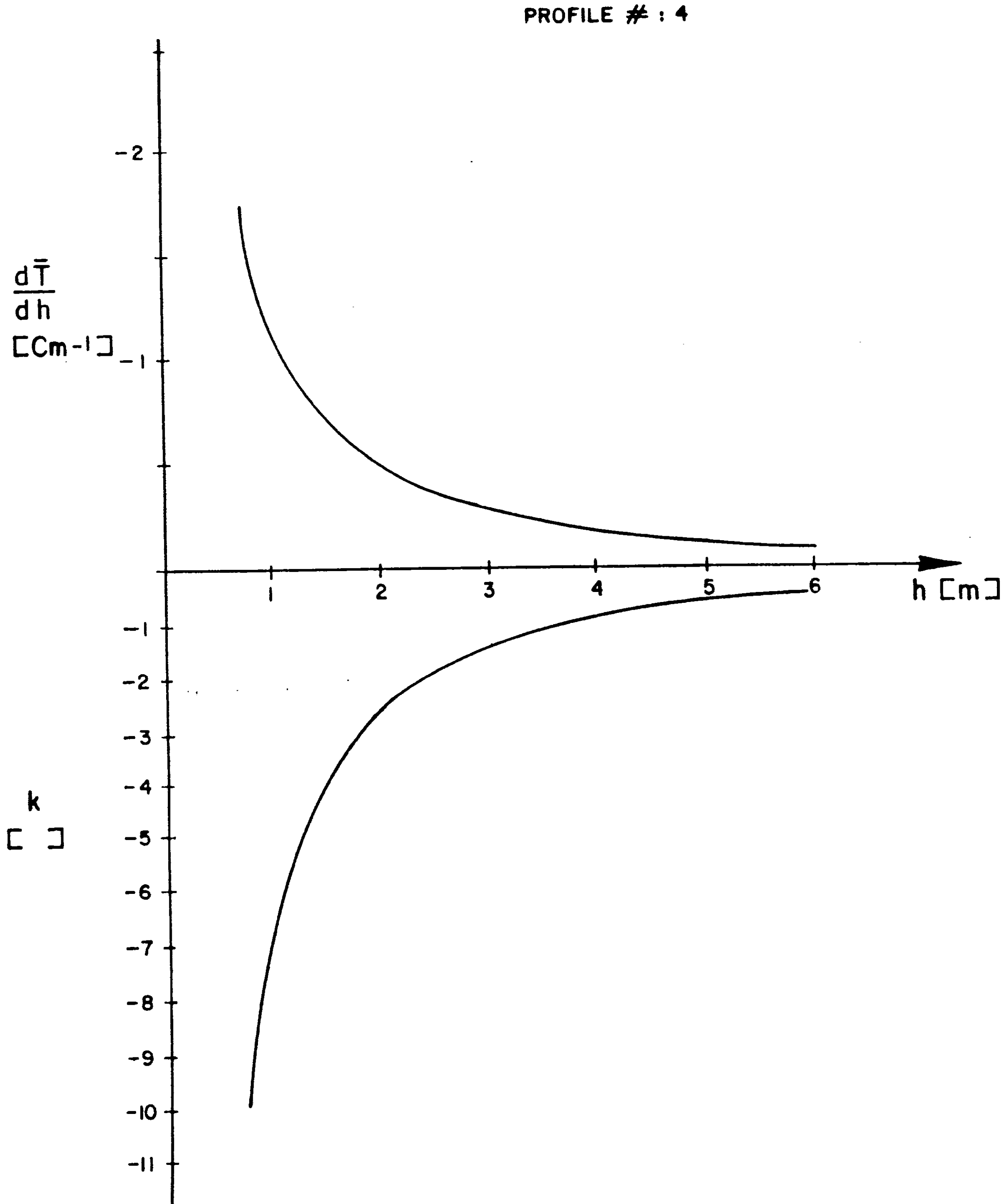


FIGURE 8

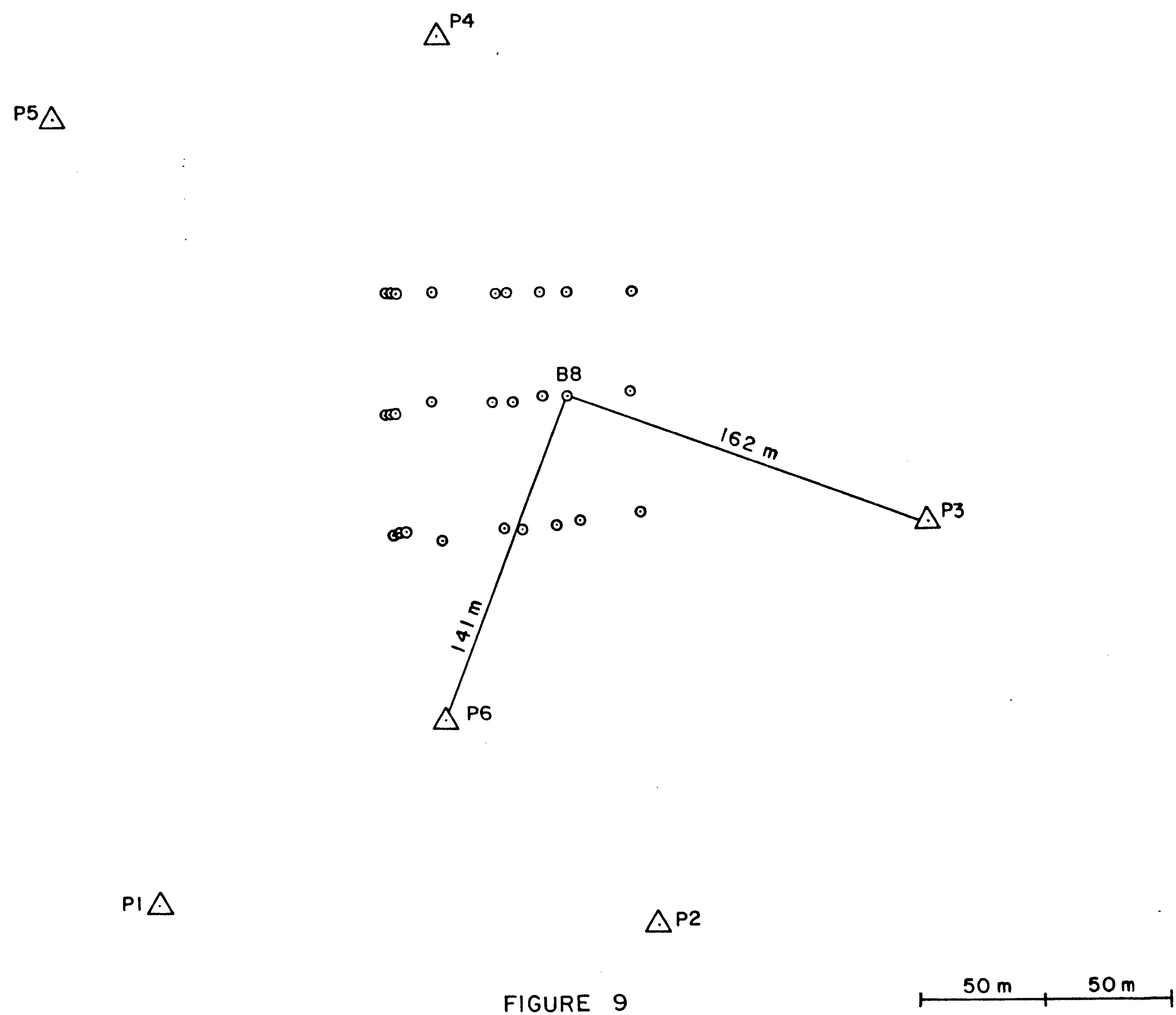
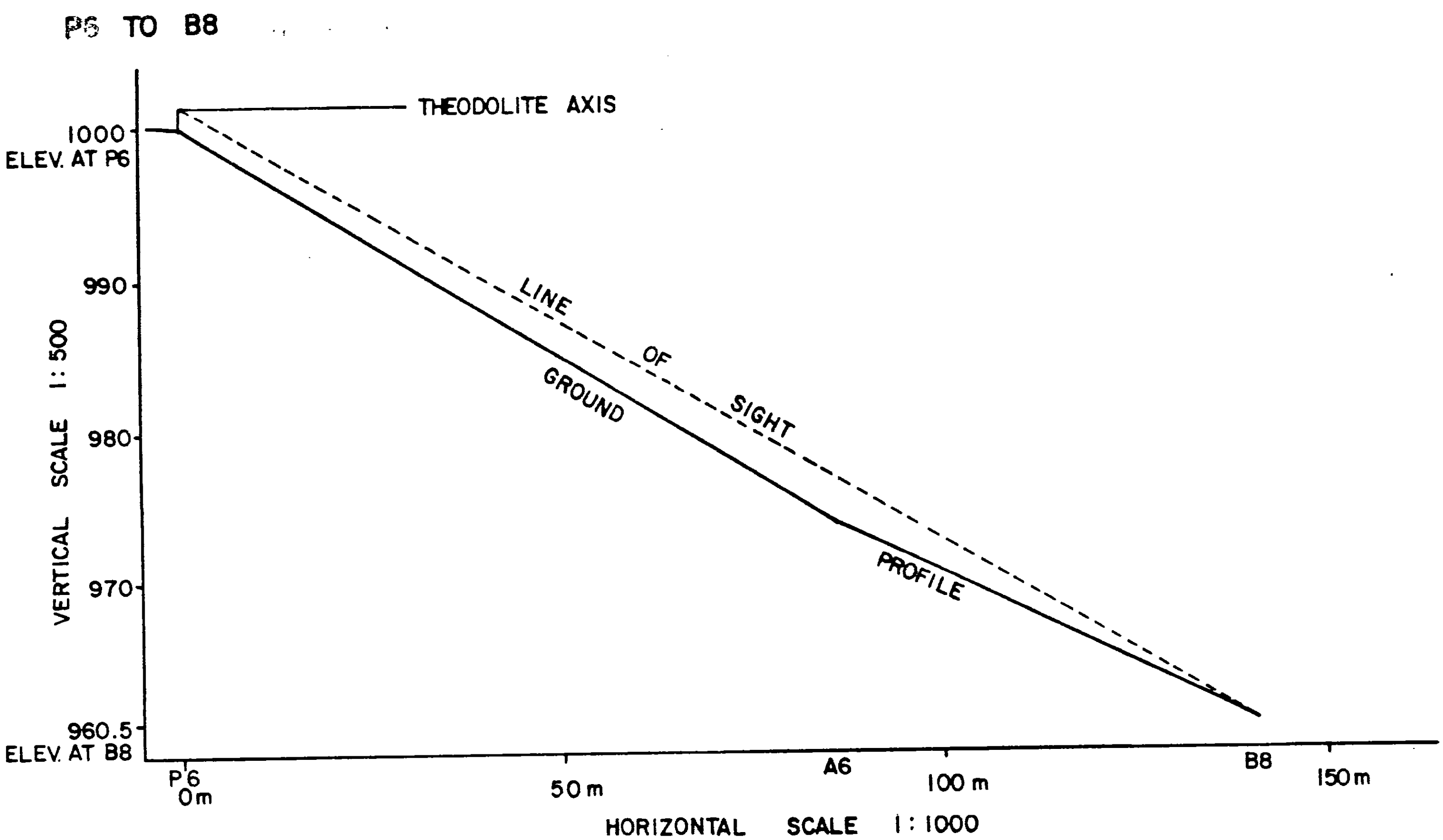
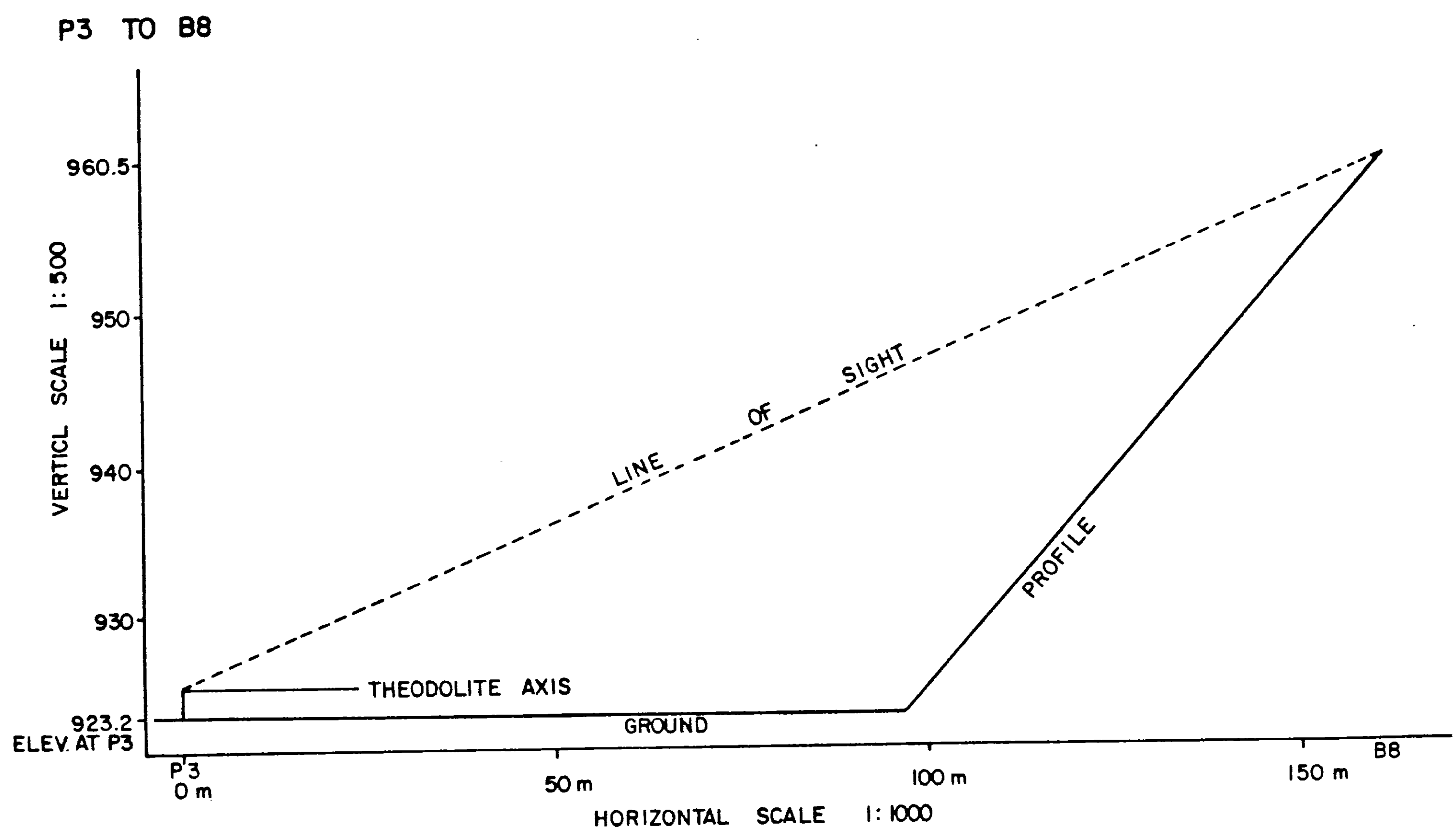


FIGURE 9


P6 TO B8
THEODOLITE AXIS
1000
ELEV. AT P6
990
980
970
960.5
ELEV. AT B8
VERTICAL SCALE 1: 500
LINE OF SIGHT
GROUND PROFILE
P6
0m
50 m
A6
100 m
B8
150m
HORIZONTAL SCALE 1:1000


P3 TO B8
960.5
950
940
930
923.2
ELEV. AT P3
VERTICL SCALE 1:500
LINE OF SIGHT
PROFILE
THEODOLITE AXIS
GROUND
P3
0 m
50 m
100 m
150 m
B8
HORIZONTAL SCALE 1:1000

FIQURE 10

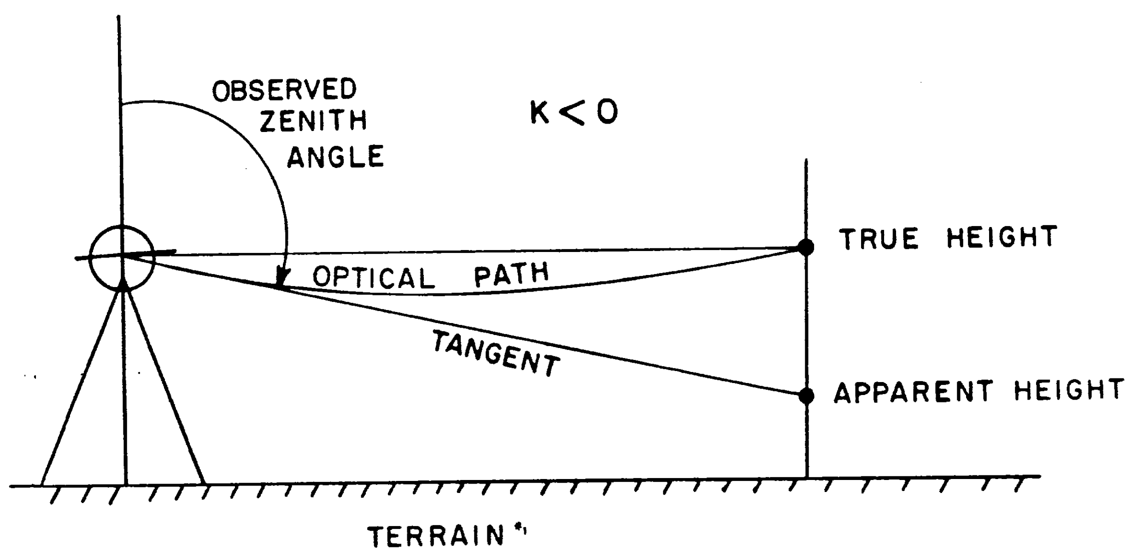


FIGURE 11

THE EFFECT OF A NEGATIVE COEFFICIENT OF REFRACTION